ANOTHER DECADE OF STRANGE QUARK MATTER (ASTRO) PHYSICS

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We present a perspective of strange quark matter research in the 1991-2001 decade focused on astrophysics topics, with particular attention to open problems. We outline the basic concepts and developments in the field, paying attention to the established research and promising perspectives. An analysis of the whole literature (experimental searches, theory, astrophysical/cosmological) serves to point out some general trends, supported by a fairy complete statistical sample of published works.

1. Introduction

The history of sciences register many cases of (almost) simultaneous works giving rise to an entirely new area of research. It is also quite common to be able to track backwards the branching of an existing area, generally much after those initial events. A less common situation is to witness that process from the start, and additionally being able to collect virtually all the papers which in turn help to, identify the main trends. Strange quark matter (SQM) belongs to this interesting category. Because of the quick development of several ideas about SQM, a benchmark event (Workshop on SQM in Physics and Astrophysics, Aarhus University, Denmark 1991) [1] made possible to join a large fraction of the active researchers in the field. Even today, and taking into account a considerable growth in the number of the latter, it would be possible to repeat the achievement (a few conferences have covered a major portion of SQM field in the following years, although other current topics were a main part of the program). Actually most of the colleagues that contributed to SQM physics/astrophysics are alive and still active, while several others enter the field each year.

In addition, and as a case study for the history of sciences, SQM presents some peculiarities worth noting. Perhaps the most notorious is that after decades of existence it is still completely speculative, yet vigorously pursued in several directions. How did this situation affected the form in which the research is done? Which are the main avenues streets and sidewalks? The purpose of this review is not to solve these problems, but rather to present an assessment of assorted astrophysics, with the aim of formulating quite clearly a few persistent questions about SQM which often remain hidden or implicit. We have no intention of writing a full review (many excellent ones have appeared over the years, see the reference list), but rather to offer a personal perspective of the evolution we have witnessed and future trends. In the present work we will focus on the last decade (1991-2001) astrophysical developments mainly. Some facts will be substantiated by a

brief (but almost complete) compilations of the bibliography of the period, available at the address www.iagusp.usp.br\ ∼mpallen in .txt form which may be considered as the electronic companion to the Aarhus compilation.

2. What is exactly strange quark matter?

The concept of elementary constituents of nucleons (quarks and gluons) is clearly central to SQM and preexists it, therefore it is useful to repeat some historical developments for completeness. With increasing center-of-mass energy, experimental searches of the elementary components (partons) of protons and other hadrons revealed a whole new realm of physics between the second half of the '60s and the early '70s. The search of a theoretical framework to engulf this body of knowledge was developed in parallel, first focused on classification schemes (or, as is called today, flavor physics) and later on finding a theory to describe the dynamics. The strong motivation given by developments of gauge theories in the '70s eventually rendered the non-abelian version based on the $SU(3)_c$ symmetry group [2] as a natural candidate for a theory of strong interactions. The new quantum number carried by the elementary constituents (quarks) was dubbed "color", and thus the dynamics involving quarks and gauge fields (gluons) become known as Quantum Chromodynamics (or QCD for short).

On the experimental side, repeated efforts to find these entities as free particles (asymptotic states) failed, and convinced most people to accept a striking feature of the theory: that the interactions preclude the appearance of the quarks and gluons outside hadrons, they are instead confined inside them. Moreover, another property was soon demonstrated to liberate quarks and gluons but only for momentum transfer scales Q^2 large enough. This is the so-called *asymptotic freedom*, and states that the colored particles behave as if they were free in the limit $Q^2 \to 0$. There is an energy (or momentum) scale above which color quantum number is not confined any more, but how large the momentum transfer should be (or in other words, which is energy, as measured by the temperature or density of the ensemble allowing the deconfinement) is still a matter of controversy. There is no doubt that the early universe passed through a deconfinement $\to$ confinement phase transition along its cooling, but there is less certainty that the densities of the "natural" laboratories (neutron stars) in which compression would deconfine hadronic matter are high enough to do so. In fact, the earliest calculations [3] using reasonable models for both the confined and deconfined phases imprinted on successive researchers the uncertain conclusion that quarks and gluons (forming a state known as the quark-gluon plasma, or QGP) should appear at densities above, say, $10 \times \rho_0$; with ρ_0 the nuclear saturation density.

The latter statement is an example of the uncertainties and types of loopholes which plagued the attempts to determine the transition points, and also the nature of the transition itself (at least when full numerical calculations [4] were out of sight). If carefully scrutinized, most of the times the conclusions are extracted from simultaneous extrapolations of both a quark model, expected to be valid for $\rho \to \infty$, and an hadronic model valid around ρ_0 but uncertain much above it. There is no certainty in either one and hence in the final result, not to talk about the "induction" of a definite order of the transition because of the adopted functional forms of the thermodynamical quantities of both sides. Nevertheless these serious and honest attempts have proliferated until today, given that the transition is still elusive (the better studied finite temperature case still has some small uncertainty in the value of T_c and a better assessment of the order, see Ref.5 for details).

Independently of the above caveats, a much radical proposal emerged to complicate even more these matters. The asymptotic freedom property guarantees that quarks and gluons will be the ground state of QCD at high densities/temperatures, but says nothing about the ground state at lower densities or temperatures. The everyday experience strongly suggests that ordinary hadrons confine the quarks/gluons and thus constitute the "true" (in the sense of $\rho \to 0$ and $T \to 0$) ground state of hadronic matter. The

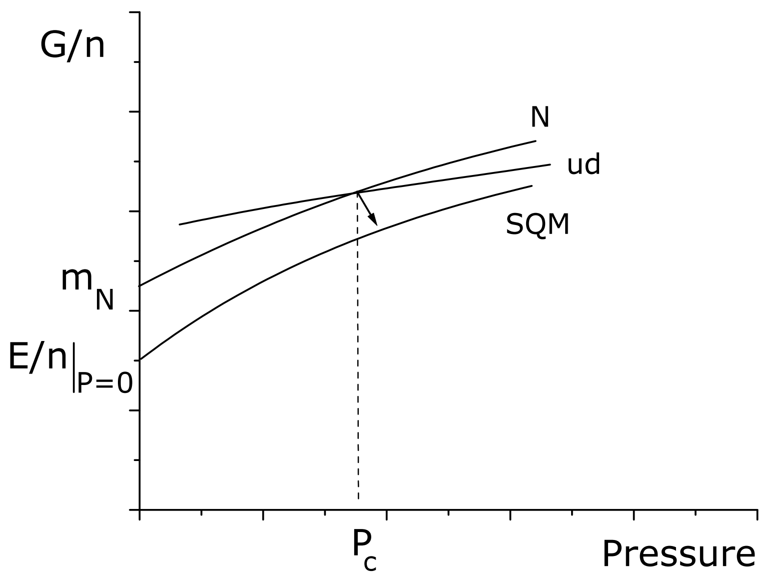

Fig. 1. The energetics of SQM. Gibbs free energy per particle G/n is shown for neutron N, two-flavor quark matter ud and strange quark matter SQM. At $P = 0$ the free energy per particle of SQM is (by hypothesis) below the mass of the neutron m_N. Although the SQM curve is always below both, its production is possible only after deconfinement of the ud matter, being suppressed by the strangeness content below P_c. The decay of ud matter to SQM is a transient depicted with an arrow and starts somewhere beyond P_c depending on the nucleation conditions.

strange matter hypothesis comes precisely to challenge this "common sense" statement: it says that the true ground state of hadronic matter is a particular form of the QGP , differing from the ordinary matter by the presence of a key quantum number (strangeness). This is counterintuitive to many people, but a careful look at the physical arguments shows no inconsistency whatsoever, at least in principle.

The argument for the SQM being the true ground state goes as follows: as is well-known the quantity that determines which phase is preferred is the Gibbs free energy per particle G/n as a function of the pressure (we impose $T = 0$ hereafter as appropriate for highly degenerate hadronic matter, it is easy to see that the term $-TS$ in the free energy disfavors SQM at high temperatures). As P is increased starting from the neighborhood of the nuclear matter saturation point ρ_0 the asymptotic freedom says that there has to be a switch from nuclear matter (N) to elementary hadronic constituents, that is, the lighter quarks u and d. The point at which this is supposed to happen has been labelled as "P_c" on the horizontal axis of Fig. 1 (therefore, the doubts stated above about the appearance of the QGP inside neutron stars may be now restated as whether the pressure at the center is larger or smaller than P_c).

However, it is here where the concept of strangeness comes in. Strangeness is the flavor quantum number carried by Λ's and other heavy hadrons. At the elementary level, it is carried by a different quark s. While creating strangeness in hadrons costs energy (because strange hadrons are heavier than non-strange ones; for instance, Λ's are heavier than neutrons and so on); this is reversed inside the QGP. The reason is simply

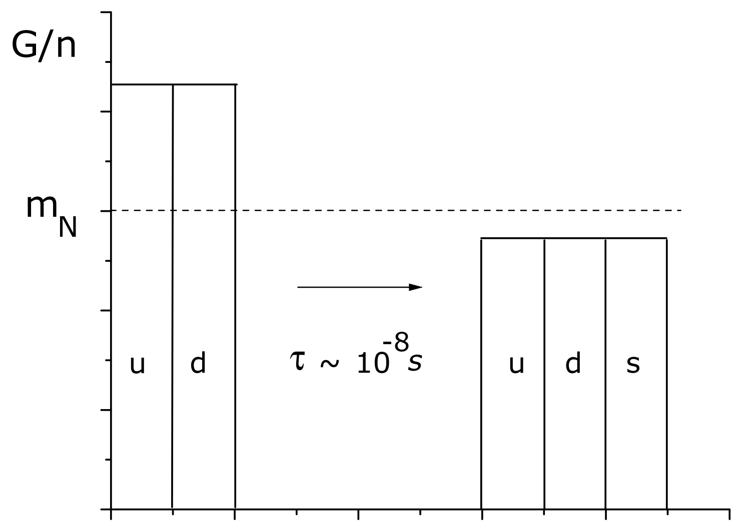

Fig. 2. Another view of the SQM hypothesis. The Fermi seas of u and d quarks lie above the neutron mass m_N initially. Because creating net strangeness lowers the energy per baryon, weak interactions will do it in a timescale of $\sim\ 10^{-8}\,s$. The energy per baryon is lower now, but the actual question related to SQM is whether G/n stays above m_N or drops below it, as shown in this graph. If the latter situation happens in dense deconfined matter, SQM would be the ground state of hadronic matter.

the Pauli exclusion principle: a new Fermi sea in the liquid (the one of the s quark) allows a rearrangement of the energy, and this sharing lowers the energy per particle. How much the gain is is not precisely known, but it is not impossible to lower the free energy per particle to a value that would be lower than the mass of the neutron m_n even when $P \rightarrow 0$. If realized, this would preclude the (strange) QGP to decay into ordinary hadrons because this would *cost* energy and the SQM would have been created. Put it simply, the compression would liberate the elementary components that quickly create its own way of surviving. We stress that all these are bulk (i.e. large number) concepts, and it is central to the SQM hypothesis to reach a strangeness per baryon of the order one (and exactly one if the strange quark had no mass to deplete its relative abundance). This is not possible in a few body system like a nucleus, because each weak decay creating a strangeness unit contributes roughly with a factor G^2_{Fermi} to the amplitude, and thus the simultaneous decays are strongly suppressed; this is why it has been very difficult to produce even doubly strange nuclei, let alone higher multiplicity ones. However, once quarks roam free in the QGP they can easily decay by $u + d \rightarrow u + s$ because there is plenty of phase space for the products until equilibrium is reached (see Fig. 2). The bulk picture has been always one way or another behind the idea of SQM.

As it stands, the SQM hypothesis is very bold. It says that everything we see around us is in a metastable state, and if conditions for creation of a large net strangeness were met, the matter would not make back ordinary hadrons (technically it is said that SQM constitutes a non-topological soliton stabilized against decays by a conserved charge,

the baryon number, see Ref. 6 for a thorough discussion of this case and related ones). The general idea of reaching extreme conditions and stabilizing the QGP is already apparent in the paper of Bodmer [7], later reintroduced and refined in references [8,9,10] and colorfully discussed in the paper of Witten [11], which was fundamental to give a big boost to SQM research.

Many applications of SQM in astrophysics were foreseen during the first decade after its official birth [11] and early infancy [12]. Since that the field has broadened a lot and a variety of problems are being studied presently. Nevertheless, key questions of SQM such as whether it does exist or not, and whether it has been ever produced in the Universe are still unsolved. On the other hand, we begin for the first time to have the possibility of falsifying these basic questions mainly thanks to the new generation of space telescopes (HST, Chandra, XMM) and neutrino observatories (SNO, Kamioka, Icecube), to name just a few.

Since astrophysical insight has shown to be essential for the study of fundamental questions related to SQM, we shall focus briefly in a few selected astrophysical problems, trying to give an assessment and pointing on the uncertainties and possible advances that may be expected in the near future.

3. SQM in supernovae

As a "natural" environment in which SQM might form, some authors have advocated for core collapse supernovae. The reasons to expect an important role of SQM there are many. First, despite of more than three decades of theoretical research and hard numerical modelling, the processes that cause the explosion of massive stars are still not understood [13]. If, as the more recent and detailed numerical simulations suggest, the neutrino-driven mechanism is fundamentally flawed, the current paradigm for explaining massive star explosions would have to be deeply revised. Although it is still too early for making definitive conclusions, investigations including the possible transition to deconfined QCD phases gain potential importance. The first studies of SQM in supernovae [14,15,16,17,18] showed that this hypothetic subnuclear energy source is more than adequate to contribute to the explosion, and that some observed characteristics in the neutrino emission of SN1987A may be naturally explained within this scenario [19,20,14]. It is worthwhile to note that a second peak in the neutrino emission is *predicted* in these models, and such signal has been tentatively associated to the late neutrinos from SN1987A detected by Kamiokande (which have to be otherwise interpreted as a statistical gap within the current paradigm). As long-term forecast, supernovae are perhaps the only astrophysical events in which we could have the possibility of making a "multiwavelength" detection (neutrinos, various electromagnetic wavelengths, gravitational waves) of the process of SQM formation. An accurate theoretical knowledge of the process of formation could allow us to presence it in real time, in case it actually occurs. However, this approach is still in its infancy, and just bold expectations have been formulated. In addition, a firmer observational background would be needed, which needs nothing more than the occurrence of a number of supernova explosions in the neighborhood of our galaxy. Second, although the general picture of SQM formation in supernovae has been qualitatively constructed, no systematic calculations have been made. There are also many unresolved questions related to strong interactions at high densities, which introduce an uncomfortable degree of uncertainty in all conclusions.

A "direct" mechanism for SNII explosion driven by SQM formation has been in fact advocated in the original papers by Benvenuto, Horvath and Vucetich [14,15]. The basics are as follows. As discussed and agreed in the literature, a seed of SQM must become active or form following the standard bounce. The interface must then propagate outwards powered by the energy release of converted neutrons, much in the same way as a laboratory combustion. It seems reasonable to assume the combustion to begin as a laminar deflagration, which quickly reaches a regime of turbulent deflagration [21,22]. It is still not clear whether the detonation mode is feasible (as originally suggested), since

it requires fast transport of heat to sustain the front. Assuming the latter case, and since the conversion is not expected to be exothermic all the way down to zero pressure, it is unavoidable that a detonation will become a standard shock wave beyond some radius (within the MIT Bag model for SQM this radius is the one for which $E - 3P = 4B$). This shock wave will propagate outwards and the question is whether or not it will be able to transfer its energy and complete the work unfinished by the unsuccessful prompt shock wave. A less extreme combustion mode (subsonic but still very fast) may be the final outcome instead of a detonation, and its propagation would mix the material on macroscopic scales due to the action of Landau-Darreius and Rayleigh-Taylor instabilities, but its role in the reenergization of the stalled shock has not been calculated as yet.

If energy can not be directly transferred to the outer layers, SQM formation may still be important because of the production of neutrinos by appropriate reactions in the deconfined phase. The binding energy of the strange star has to be released as well [23] , much in the same way as the binding energy of the neutron star in the standard picture. Although new fresh neutrinos could in principle produce a late revival of the stalled shock wave, other features than the total released energy are essential such as spectral features of the neutrino emission, and more importantly (if the transition happens to be somewhat delayed) the exact time of its occurrence, since if it occurs too late there will be no way to explode the star by the shock reheating mechanism at all.

A better understanding of the previous sequence of combustion processes will also give information about the timescale of the conversion of the star, which is closely related to the different observational signals. These calculations are yet to be performed in detail and constitute a priority task for the near future.

4. Delayed conversions, compact star structure and gamma-ray bursts

If the just-born protoneutron star (PSN) does not collapse to a black hole due to accretion in the early stages [24], and it happens that SQM is absolutely stable (i.e. the true ground state at zero pressure) then pure strange stars, made up entirely of strange quark matter from the center to the surface, may be the compact remnants of supernovae. In the case of absolute stability, if the transition is *not* triggered during the supernova explosion, all "normal" neutron stars would be in a metastable state, which is quite difficult to imagine because of ISM contamination arguments [25,26,27] and the mismatch $\tau_{conv} \ll \tau_{star}$ between the timescale in which favorable conditions for conversion occurs τ_{conv} and the lifetime of the star τ_{star}. According to recent calculations the deconfinement transition is more likely to occur by heating and compression during the Kelvin-Helmholtz phase of proto-neutron star (PSN) evolution (see, for instance, Ref. 28). If it did not happen there, once the PNS has cooled to temperatures below $\sim 1MeV$, only accretion from a companion star or strangelet contamination would allow the transition (and many barriers may preclude its occurrence), even in the case where it is energetically favored. Thus, the existence of strange stars is determined not only by fundamental questions concerning the true ground state of dense matter but also by the exact physical conditions in the specific astrophysical environments together with the plausibility of the conversion mechanisms in these situations.

Other interesting questions are related with the emission of gamma-ray bursts associated with the conversion process. Many works in the past have explored the idea that the conversion of NM into SQM in NSs may be an energy source for GRBs [29,30,31,32,23,33,34]. These models addressed spherically symmetric conversions of the whole NS rendering isotropic gamma emission. These models are still very schematic to address the more difficult questions, and many of them tend to ignore, for instance, the so-called baryon load problem, briefly stated as the smallness of baryons in the ejected flux as a precondition to avoid degradation of the energy to softer bands. Accumulating observational evidence suggests that at least "long" GRBs are strongly asymmetric, jet-like outflows, a feature that needs some crucial ingredient in the SQM physics for-

mation/propagation to proceed. To be sure, the "short" burst subclass is not obviously asymmetric, and they may actually be spherically symmetric if the sources are close enough.

A new potentially important feature recently recognized [22] is that if a conversion to SQM actually begins near the center of an NS, the presence of a moderate magnetic field B ($\sim 10^{13}$ G) will originate a prompt *asymmetric* gamma emission, which may be observed as a short, beamed GRB after the recovery of a fraction of the neutrino energy via $\nu\bar{\nu} \rightarrow e^{+}e- \rightarrow \gamma\gamma$. The basic physical effect is that the influence of the magnetic field expected to be present in NS interiors quenches the growth of the hydrodynamic instabilities in the equatorial direction of the star (parallel to the magnetic field) while it allows them to grow in the polar one. As a result, the flame will propagate much faster in the polar direction, and this will result in a strong (transitory) asymmetry in the geometry of the just formed core of hot SQM, which will resemble a cylinder orientated in the direction of the magnetic poles of the NS. While it lasts, this geometrical asymmetry gives rise to a bipolar emission of the thermal neutrino-antineutrino pairs produced in the process of SQM formation. This is because almost all the thermal neutrinos generated in the process of SQM formation will be emitted in a free streaming regime through the polar cap surface, and not in other directions due to the opacity of the matter surrounding the cylinder. The neutrino-antineutrino pairs annihilate into electron-positron pairs just above the polar caps of the NS, giving rise to a relativistic fireball, thus providing a suitable form of energy transport and conversion to gamma-emission that may be associated to short gamma-ray bursts. A unifying scheme in which SQM appearance produces spherical ejection phenomena to highly asymmetric gamma beaming, as a more or less continuous function of the magnetic field B and the astrophysical system under examination may be possible, and is tentatively sketched in Table 1.

Table 1. Possible outcomes of SQM burning in stellar systems

Mag. field (G)	Type II SN	LMXB-HMXB*	AIC(?)†
$0 < B < 10^{12}$	"normal" SN	spherical, weak short GRB	UV-X flash
$B \sim 10^{13}$	bipolar SN	bipolar,strong short GRB	bipolar UV-X flash
$B \geq 10^{14}$	?	jet-like, weak short GRB	jet-like UV-X flash
$B \gg 10^{15-16}$	–	-no SQM formation-	–

∗ only if $NM \rightarrow SQM$ conversion is sometimes suppressed when a NS is formed.
† upper limit to the rate $\sim 10^{-4} yr^{-1} galaxy^{-1}$ needs to be revised if SQM burning occurs modifying nucleosynthetic yields.

5. Detection of SQM

Although the present work has been intentionally biased towards the astrophysical aspects of SQM, the importance of laboratory experiments can not be overstated. The main well-known disadvantage of heavy ion collision experiments for the search of SQM production is clearly the high-temperature environment, which tends to destabilize small SQM chunks (strangelets) and render their production difficult. In addition, even if produced, the "dirty" high particle multiplicity environments makes the identification of strangelets a complicated business. However, the recent claims [35] for QGP production already before the RHIC runs (see Ref. 36 and the literature therein) and the monotonic trend of the observables in support of the former should revive the interest in strangelet physics, given the the precondition of QGP formation seem likely.

An alternative for the direct detection relies on the improvement of detector analysis in a variety of cosmic rays and related experiments. For example, the prospects for the space-based spectrometer AMS are encouraging [37] since exciting claims about nuggets crossing the earth have been issued [38] and merit a closer examination.

Returning to the stellar astrophysics, SQM may be "detected" in a binary system when lines observed from one member of the source allows in some cases a determination of the mass M and redshift z, and thus a knowledge of the radius R (the same idea has been used in the '20s to determine structure of WDs). Previous work using the redshift of spectral lines involved mainly isolated NSs, like the exciting announcement of Cottam, Paerels and Méndez [39] of a redshift $z = 0.35$ detected in the bursting source EXO 0748-676 spectrum. Contrary to the naivest analysis, we must stress that this determination does not exclude at all a SS as a candidate as claimed in the latter work, because we can not still pin down the type of viable SS models (see Ref. 40). It is probably more accurate to state that if the source redshift determination is correct and a SS model is constructed for it, then SQM would produce very compact sources for very low values of the mass only (see Ref. 41).

The most promising advances in the detection of SQM are those related to the observation of compact star structure and cooling. The goal is to determine whether NS are composed of ordinary beta-stable nuclear matter or contain QCD phases in their interior. This has a direct observable impact on the global static properties of the star (such as the mass-radius relationship) and in the short and long term cooling history of these objects. Briefly, objects with QCD phases inside them tend to have smaller radius and to cool faster than beta-stable nuclear matter objects of the same mass. Some mass and radius determinations made up to date, have yielded values around 1 solar mass and $\sim 7km$ (e.g. the sources Her X-1 [42] and SAX J1808.4-3658 [43]). Other sources offer better determinations but are still controversial (RXJ 1856-37 [44] and EXO 0748-676 [39] mentioned above, among a few others). There are some tentative indications that the value of the surface temperature of some objects (e.g. 3C58, Vela, Geminga) cannot be completely understood in terms of the standard cooling theory (see Ref. 45 and references therein). Therefore, it has been argued that these objects cannot be normal neutron stars and should have exotic phases in their interior. Many unresolved questions are relevant in connection with this picture, since they are expected to have strong impact in the observational output (see Ref. 46 for discussion). These include the appearance of superfluidity in dense stellar matter, a deeper understanding of the QCD phase diagram in the high density regime, the improvement of phenomenological models for strong interactions at finite density, a comprehension of the dynamics of a possible hadron-quark phase transition in stellar conditions and an evaluation of the related consequences and signatures in each specific astrophysical context.

6. Surprises on the microscopic state of SQM

The very basic picture of SQM as a Fermi liquid confined by some parametric ingredient (generally put by hand) leaves lots of room for improvements and questioning. Asymptotic freedom is expected to drive the system beyond a certain density that can not be reliably determined today. It is quite natural to expect that a more complex picture will emerge when a closer look to the system is taken. For example, while *correlations* between quarks are certainly expected in the hadronic phase and immediately above the deconfinement point [47], the role of two-quark states known as *diquarks* did not receive much attention until a few papers [48] pointed out how useful they may be in the description of dense stellar matter. Simple models were constructed in the spirit of a partial bosonization of the quark phase, and the corresponding stellar sequences studied. Later, a revival of the study of QCD pairing leaded to identify some interesting possibilities (two-flavor superconductor -2SC- and color-flavor locked -CFL- state) that gave a whole new twist to the description of dense matter [49]. It is currently believed that the CFL state is energetically favorable over the 2SC and therefore may comprise a large part of stellar interiors. An important point related to our discussion is the recognition of the possible role of pairing in the absolute stability of matter. Detailed calculations performed for strangelets [50] and bulk strange matter [51] showed the substantial enlargement of the stability window (Fig. 3) due to the action of the gap energy Δ when compared

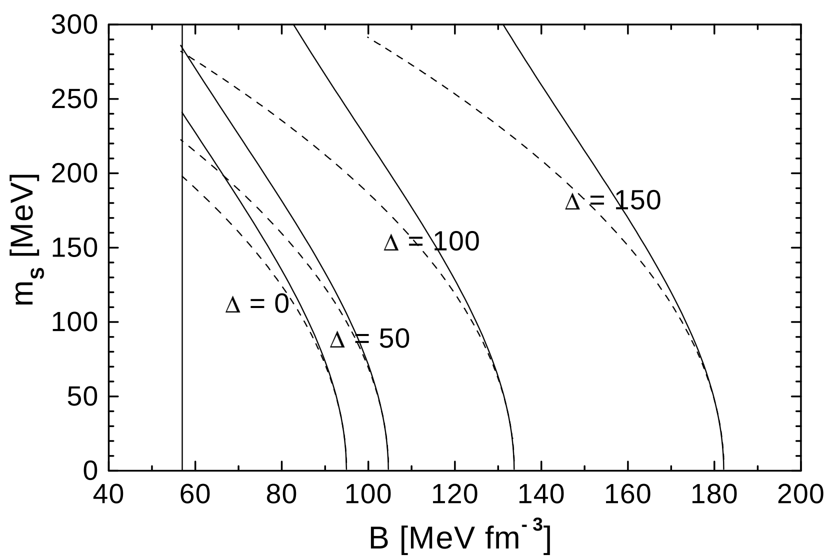

Fig. 3. The window of stability of CFL strange matter. Room for an absolutely stable CFL state lies between the boundaries. Each window refers to a given value of the gap Δ as in indicated. The regions are much wider than the ones found for SQM[12]. The dashed lines display the approximated result to order m_s^2, as discussed in Ref. 51.

with the gapless state. This "color-flavor locked strange matter" allowed the calculation of self-bound stars constructed with parametric equations of state in Refs.[52,53].

A discussion of the effects of a sudden release of this extra energy has been presented by Hong, Hsu and Sannino [54] and subsequently criticized by Blaschke et al. [55]. The main issue whether the pairing, acting immediately after deconfinement, will release the energy in a "useful" form (i.e., to power a supernova), a question which is also related to the timescale of this event. In any case neutrinos would be produced and their (sudden) release add to the energy budget, as advocated in Ref. 56.

Even when acknowledged that the physical description of the CFL state is still crude, it is important to have in mind that substantial surprises may be hidden in the high-density region of the QCD phase diagram, with all their implications for astrophysical studies.

7. Types of published contributions to SQM and their challenges

Given the different situations in which SQM may be important, it may be asked how does the literature published on SQM reflect that trends. It can be said that the "birth" (prior to 1984) and "early infancy" ($\geq$ 1984) papers already shown the general spirit of the later work in the field, which in essence has not changed substantially but altered somewhat their proportional weights. Generally speaking, and following these pioneer efforts, follow-up papers may be classified according to their content in a) papers trying to address the stability itself (generally within a model calculation) and SQM physical properties; b) papers devoted to the search of SQM in laboratory and related environments c) papers dealing with astrophysical/cosmological SQM, including observations which may help to prove/disprove the SQM presence far away from the laboratories. All three things

are quite difficult to argue, but for different reasons. The class a) needs to convince the community that the models/calculations are as accurate as $\sim 1\,\%$, since the difference $(m_n - E/n)_{P=0}$ is not expected to be larger than few tens of MeVs. Class b) works by ever closing windows in the parameter space, although loopholes in the experimental settings or measurements may be found from time to time (and in fact they are, an event that shifts the excluded region in a significative manner). Finally, class c) suffer from both the uncertainties of the astronomical measurements themselves and also from the danger that colleagues astronomers devise an interpretation at least as solid as the SQM-based one but invoking more conventional physics (a task which generally takes a short time after the observation being reported). In other words, and in spite of serious attempts to find the Holy Grail of SQM physics, we still lack of convincing evidence of its reality, a statement that also applies to any clear-cut astrophysical/cosmological crucial test hitherto proposed. One positive tendency, related to the degree of maturity of the field, is the increasing number of realistic models that going well beyond the basic SQM properties attempt a fine comparison and sometimes a synthesis to fit in the observed phenomena. A clear example of this attempts (not fully successful as yet) is the efforts to understand the room for strange stars in the compact object zoo [57]. As previously mentioned, direct search in space is an exciting perspective because large flux estimates have been obtained [58].

8. Statistics, facts and outlook

Can we visualize any definite trend in the literature and forecast somewhat the future of SQM ? The answer may depend on what exactly is focused. The first interesting point to notice is that the research papers in SQM have grown beyond an expected vegetative rate, perhaps reflecting the growth in the number of people involved in sciences overall and the attractive of a "magnet" field. The absolute number of papers (390) directly dealing with SQM in the last decade (1992-2001) is shown in Fig. 4. There is a smooth continuous growth of $\sim 70\%$ in this number of papers respect to the previous decade, to be compared with the absolute number (223) in the previous Aarhus compilation comprising the period 1969-1991. The lower bars in Fig. 4 correspond to the papers classified as c), which have grown from about 1/3 of the total at the beginning of the decade to more than one-half in the latest years (with a peak of $\sim 2/3$ in year 2000). However, it is interesting to note that class c) papers already comprised a $\sim 60\%$ of the total at the time of the Aarhus compilation. This means that after some years in which the astrophysical/cosmological papers lost their leadership, the situation bounced back to the pre-1991 average value. On naïve grounds, an outsider physicist just aware of the status of SQM would have expected the predominance of type b) based on the referred lack of experimental/observational confirmation of the SQM existence [59]. To be sure, class c) papers do address to some extent this issue indirectly, but the importance of the experimental evidence can never be overstated. Our impression is that, unless evidence for SQM is available along the first decade of the XXI century, there would be a decline (not just a slowdown of the growth rate). It is however quite clear that announcements of data which is difficult to interpret within conventional hadronic models (see previous sections) may, if sustained, give a substantial impulse to SQM, taking the place of the laboratory data to a large extent. Indeed, it is not impossible that physical features preclude the laboratory detection for indefinite time but astrophysical/cosmological evidence becomes available. It is not easy to foresee what kind of trend would this hypothetic situation (i.e. lack of laboratory evidence but definite astrophysical hints) could create. The case would resemble, for instance, the theory of matter inside the white dwarfs, never produced in laboratory but widely accepted by all astrophysicists.

As a concluding remark we should add that SQM is to some of us a fundamental issue too important to be dismissed (or confirmed) at present. Even if proved to be wrong, the SQM hypothesis has stimulated a deep analysis by theoreticians and experimentalists as well that goes much beyond the very limited subject. This facts together with

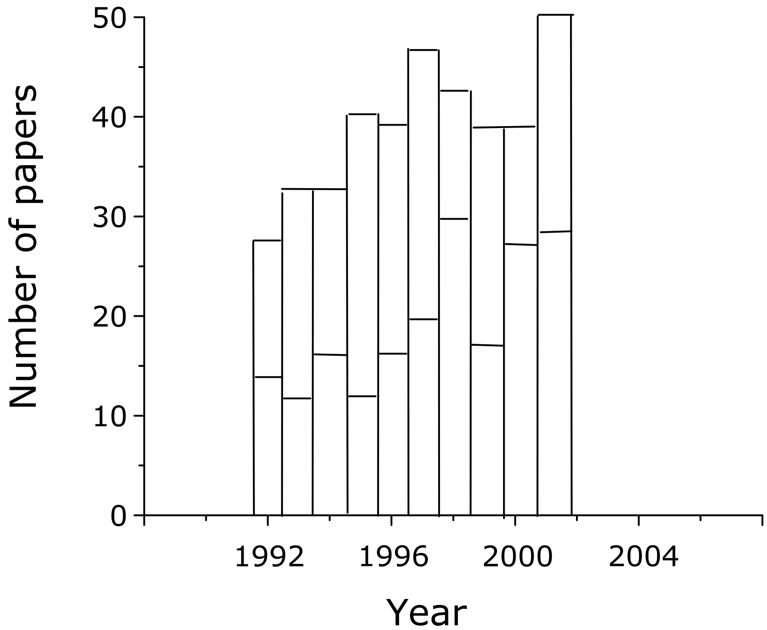

Fig. 4. The number of SQM papers 1992-2001. The marks in each bar shows the number of type c) papers dealing with astrophysics/cosmology. It should be remarked that the selection has not been extremely rigorous to avoid the omission of some contributions helpful for those interested in the full listing. This means that no distinction has been made between,say, proceeding and journal papers (often containing the same results) for the sake of completeness. The sources (SPIRES, Web of Science, ADS and a few others) are well-known extensively used databases, and the completeness of the sample is likely to be $> 95\%$, which allows to draw safe conclusions and locate the searched material in most cases. Any omitted contributions, specially from less visible sources, may be communicated to the authors to be included in the list.

several unique features present in the development of the field has provided, and would likely provide, an excellent opportunity to learn about nature and the way knowledge is constructed in a vivid and fruitful fashion.

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